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Determination of the fire hazards of mine materials using a radiant panel

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Abstract

The objective of this study was to develop a laboratory-scale method to rank the ignition and fire hazards of commonly used underground mine materials and to eliminate the need for the expensive large-scale tests that are currently being used. A radiant-panel apparatus was used to determine the materials' relevant thermal characteristics: time to ignition, critical heat flux for ignition, heat of gasification, and mass-loss rate. Three thermal parameters, *TRP*, *TP1* and *TP4*, were derived from the data, then developed and subsequently used to rank the combined ignition and fire hazards of the combustible materials from low hazard to high hazard. The results compared favorably with the thermal and ignition hazards of similar materials reported in the literature and support this approach as a simpler one for quantifying these combustible hazards.

Introduction

The potential fire hazards from combustible mine materials is of major concern as they can have substantial impact on the safety of mine workers. Combustible materials tend to be solids, and within this category there exist degrees of flammability and fire resistance. These materials may be readily ignitable, or they may be able to withstand high temperatures and high heat fluxes. Presently, no simple methodology exists to assess these possible fire behaviors and quantify the resultant fire hazards. Thus, better knowledge of the thermal properties and chemical characteristics of combustible materials is of great importance to the safety of mine workers. Tewarson (1994) developed a methodology that he subsequently used to evaluate the ignition and fire-resistance properties of combustible mine materials, but these efforts are more than 20 years old and do not include many of the new materials used in mines today. The standard practice that has evolved for a combustible material to be approved by the U.S. Mine Safety and Health Administration for use in underground coal mines is to conduct extensive and costly large-scale experiments on each new material that is used in a particular mine operation. The results of such tests provide pass/fail answers to the questions of a material's flammability or fire resistance, yet they provide little, if any, information that will lead to a better understanding of the basic mechanisms involved. Therefore, there is a need to quantify material flammability properties and to develop a

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methodology to rank the ignition and fire hazards of commonly used underground mine materials.

During the heating and ignition stages of combustible materials, properties such as smolder susceptibility, minimum surface temperature for ignition, thermal conductivity, heat capacity, density, and heat of gasification are known to be important (Apte, 2006). During the flaming stage, additional parameters such as the heat of combustion, heat release rate, flame spread rate, yields of soot/smoke, and toxic gas production become more important as the flame is sustained and spreads. In general terms, the heat flux incident on the surface of a solid combustible controls not only the rate of temperature increase of the local fuel surfaces, resulting in the expulsion of fuel vapors that sustain the flaming process, but also the heating of other combustible surfaces that subsequently ignite and spread flame.

To simulate a solid combustible exposed to an external heat flux, the National Institute for Occupational Safety and Health (NIOSH) used a radiant-panel apparatus to determine times to ignition, mass loss rates, heats of gasification, and minimum, or critical, heat fluxes required for ignition of the fuel vapors liberated from the combustible surface. Three thermal parameters, *TRP*, *TP1* and *TP4*, were derived from the data obtained during these experiments and two of those parameters, *TP1* and *TP4*, were subsequently used to rank the combined ignition and fire-intensity hazards of the combustible materials from low hazard to high hazard. The heats of combustion, H_c, used in these parameters were obtained independently using the oxygen bomb calorimeter technique described in detail by Jessup (1960). The following sections describe the construction and operation of the radiant panel, how the experiments were conducted and the results of the radiant-panel experiments, and discuss how these results may be applied to determine the acceptability of combustible materials for use in mines.

Experimental

A radiant-panel apparatus was constructed to determine the various combustion properties of the mine materials during the thermal decomposition and ignition stages of combustion. A metal structure was fabricated to serve as the base frame for the test apparatus. Two layers of high-temperature millboard, each 6 mm (0.25 in.) thick, were installed to provide a barrier between the radiant heater and the test frame, and to protect the surroundings from heat generated by the radiant panel. The radiant panel selected for this application, a Raymax 2030, was mounted vertically and directly in front of the millboard, attached to the base frame. A 240-V, single-phase, variable-output transformer provided electrical power to the radiant panel. Eight type K thermocouples were installed in the fume stack above the apparatus to measure the gas temperatures. A gas sampling tube connected to carbon monoxide (CO) and carbon dioxide (CO_2) analyzers measured the amount of CO and CO_2 generated during testing. The radiant panel apparatus is shown in Fig. 1.

Prior to the material testing, the radiant panel was calibrated using a Hukseflux USA1 heat flux gauge. The gauge was mounted horizontally, 5 cm (2 in.) from the center of the radiant panel, to measure the heat flux as a function of applied voltages to the radiant panel (Fig. 2).

Sixteen materials were selected for testing: four brattice materials, two sealants, seven conveyor beltings made of either polyvinyl chloride (PVC) or styrene-butadiene rubber (SBR), and three woods. For the wood and conveyor-belt materials, a pilot hole measuring 6 mm (0.25 in.) in diameter by 6 cm (2.25 in.) deep was drilled into the material to accommodate the metal stand used to hold the material in place during the test. For the brattice, a material holder was designed with metal clips to hold the material in place. For the foam sealant material, a holder was designed with a thin rod to hold the material. Figure 3 shows one of the metal stands with the sample material in place.

Each material was weighed and fastened to the holder. The test holder and material were placed on a load cell, 5 cm (2 in.) from the radiant panel. The load cell was used to determine the weight loss of the material over time for each test. A pilot flame was located just above the material to ignite the flammable gases emitted from the material. Power to the radiant panel was turned on to begin the test. If the material ignited before 5 min had elapsed, the time would be recorded and noted as ignition time. If the specimen failed to ignite after 5 min had elapsed, the test was considered complete and recorded as a non-ignition. If the pilot flame extinguished during the test, a note was made of this and the test repeated. The test was repeated with a new sample of the material at heat fluxes above and below the initial test heat flux to determine the minimum heat flux required for ignition, time to ignition, and mass loss rates at the various heat fluxes. These parameters were then used to calculate the heats of gasification and three thermal parameters that were used to rank the materials from low thermal hazard to high thermal hazard. Low-hazard materials are relatively difficult to ignite, and if ignited, do not burn vigorously, while high-hazard materials ignite easily, and once ignited, burn vigorously.

Theory

For a solid surface, assumed to be of semi-infinite thickness, the surface temperature, T_s, as a function of time, t, when exposed to a constant external radiant heat flux, q''_e, is given by the expression (Carslaw, 1959):

$$T_s = T_0 + q''_e [4t/(\pi \kappa \rho c_p)]^{1/2} \quad (1)$$

where T_0 is the initial surface temperature in K, κ is the solid thermal conductivity in kW/(m-K), ρ is the density of the solid in g/m^3, c_p is the heat capacity of the solid in kJ/(g-K) and q''_e is in kW/m^2.

As the surface temperature and the temperature of the solid mass beneath the surface begin to increase, the solid begins to thermally decompose, resulting in the expulsion of fuel vapors at the surface. If the heat flux is sufficiently high, then at some point sufficient fuel is generated to form a flammable mixture at the surface and this mixture subsequently ignites. If the surface temperature at the instant of ignition is defined to be T_{ig}, then a lumped parameter containing the material thermal properties can be defined as a thermal response parameter named *TRP* (Tewarson, 1994), given by:

$$TRP=(T_{ig}-T_0)\cdot(\kappa\rho c_p)^{1/2} \quad (2)$$

Substituting Eq. (2) into Eq. (1) and rearranging yields the alternate expression in terms of measurable quantities:

$$TRP=(4/\pi)^{1/2}\cdot q_e''\cdot(t_{ig})^{1/2} \quad (3)$$

where t_{ig} is the time in seconds at which the combustible fuel vapors ignite above the surface of the solid. The smaller the value of *TRP*, the easier it is for the material to ignite and subsequently burn and, as a result, the hazard associated with the ignition process should vary in some inverse manner with *TRP*.

Once ignition occurs, the surface of the combustible burns, generating heat, and if extensive enough, results in flame spreading across the surface, producing an ever-increasing heat release rate, Q_f. The resulting Q_f in kW is proportional to the mass generation rate of fuel vapors and the heat of combustion of the solid:

$$Q_f=m_f''\cdot A_s\cdot H_c \quad (4)$$

where m_f'' is the mass flux of fuel vapors from the solid surface in g/(m^2-sec), A_s is the sample surface area in m^2 and H_c is the heat of combustion of the solid combustible in kJ/g.

The magnitude of the heat release rate depends upon the rate at which the solid decomposes, producing fuel at the surface, and this rate of fuel production depends, in turn, on the rate at which the solid is being heated. During active burning, the rate at which the surface is heated is due primarily to the radiative heat to the surface that is continuously supplied by the flame. In order to assess the levels of mass flux that can be generated from one material to the next and, hence, the levels of heat that can be produced from a flaming fire, the use of another combustible property, the heat of gasification, h_g, in kJ/g can be used. The heat of gasification is defined as the ratio of incident heat flux to the mass flux of fuel vapors:

$$h_g=q_e''/m_f'' \quad (5)$$

By measuring the mass loss rate of the solid combustibles at different levels of incident heat flux, the heats of gasification for each can be determined, and for the heat fluxes actually encountered during flaming combustion, the mass flux will vary inversely with h_g. Consequently, for different materials the relative heat release rates that would result from the burning of a constant combustible surface area are proportional to the ratio of heat release rate to heat of gasification:

$$Q_f \propto H_c/h_g \quad (6)$$

During an active flaming fire, the hazard will increase as the heat release rate increases, and for different combustible materials, the hazard will vary with the size of fire that can be

generated from that material. Consequently, the hazard will increase as the ratio H_c/h_g increases.

If the ignition hazard and the flaming hazard are combined into one hazard parameter, then this parameter would vary directly with Eq. (6) and inversely with *TRP*, as defined in Eqs. (2) and (3). At the very minimum, two possibilities exist: that the combined hazard varies in a multiplicative manner or in an additive manner. For the multiplicative case, the thermal parameter *TP1* is given by:

$$TP1 = 10^4 H_c/(h_g \cdot TRP) \quad (7)$$

For the additive alternative, the thermal parameter *TP4* is given by:

$$TP4 = 10H_c/h_g + 100H_c/TRP \quad (8)$$

Both of these parameters scale in the same manner, and in the following section, the use of these parameters to define the combined relative thermal hazards of ignition and fire intensity will be calculated and compared for the materials tested in this study.

Results and discussion

In the experiments, the time for a small pilot flame to ignite combustible vapors generated from the surface of the various samples was measured over a range of external incident heat fluxes, along with the average mass loss rate for each sample and each experiment. A total of 94 experiments were conducted, involving 16 different combustible materials and at heat fluxes that varied from a low of 10 kW/m^2 to a high of 26 kW/m^2. The average values for h_g and *TRP*, calculated from these measurements, along with the values of H_c and the minimum heat flux for ignition, $(\dot{q}''_e)_{crit}$, are shown in Table 1. It is worth noting that the *TRP* values obtained here are in reasonable agreement with those obtained by Tewarson (1994) for similar materials.

For each experiment, the thermal parameters *TP1* and *TP4*, defined in the previous section, can also be calculated from the measured heats of gasification, thermal response parameters and heats of combustion. The average values obtained for each combustible material are shown in Table 2, and it should be noted that these values were not calculated using the average values of h_g and *TRP* from Table 1 but from the data from all experiments with each material.

The average thermal parameter values shown in Table 2 vary over a fairly large dynamic range, and it is not clear just from the tabular values if either *TP1* or *TP4* is a better measure than the other, or if there is any appreciable difference, for the combined hazards of ignition and fire intensity. To assess how each of these parameters scaled with the other, *TP4* was plotted against *TP1* (Fig. 4). From Fig. 4, it is apparent that both parameters correlate and that, in defining a combined parameter that represents an estimate of the combined hazard, it makes little difference which one is chosen. This result can also be demonstrated by ranking

the various materials from low hazard to high hazard based upon the values of either *TP1* or *TP4*. In order to show this comparison, the samples are designated with numbers 1 through 16 and then ranked from low hazard to high hazard based upon their respective values of *TP1* and *TP4*. The results of this ranking are shown in Table 3.

Based upon this comparison, one of the line brattices tested, sample No. 4, represents the lowest hazard while one of the sealants, sample No. 6, represents the highest hazard. It is also worth noting from Table 1 that sample No. 4 also had one of the highest critical heat fluxes for ignition (20 kW/m^2) while sample No. 6 had one of the lowest values (12 kW/m^2). Finally, it is worth noting that the wood samples ranked on the high end of the hazard comparison and that oak was ranked somewhat less hazardous than either of the pine woods tested.

Summary and discussion

Based upon the above results and analysis, it appears reasonable that a simple laboratory test using a radiant panel to provide constant heat fluxes at material surfaces, combined with measurements of the mass loss rates and times to ignite the flammable vapors, represents a viable technique for assessing the relative hazards of ignition and fire intensity for a variety of combustible materials used in underground mines. To further apply this technique in terms of potentially accepting materials based upon their respective values of either *TP1* or *TP4*, it would appear that materials with *TP1* values less than about 100 or *TP4* values less than 35 would qualify as “acceptable” while materials with respective higher values would entail larger fire risk hazards and consequently be rated as “unacceptable.” Using these criteria, out of the 16 materials tested, six of the seven conveyor belts and only two of the four brattice cloths would be deemed acceptable. Both of the tested sealants and the three woods would be unacceptable. This cutoff is subject to additional testing and refinement, and also should be weighted by additional hazards of toxicity and visibility that may result from the gases and smoke liberated from the materials.

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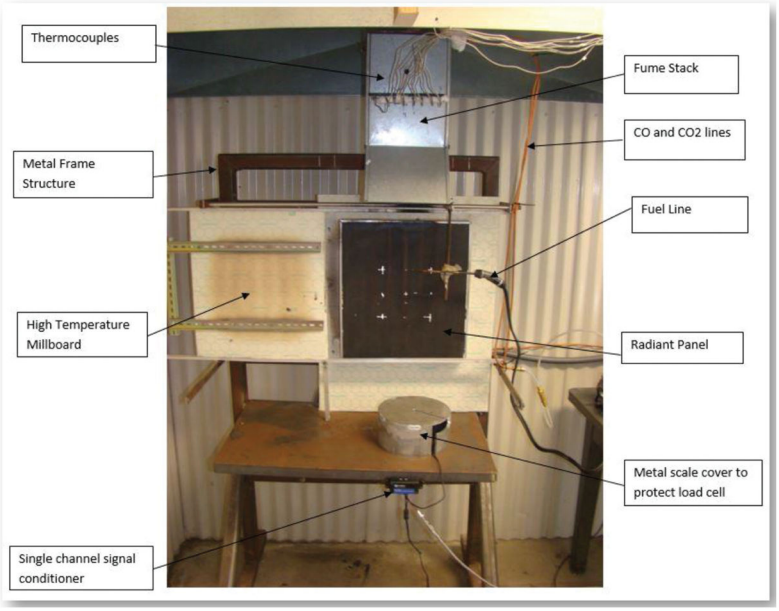

Figure 1.
Radiant-panel apparatus.

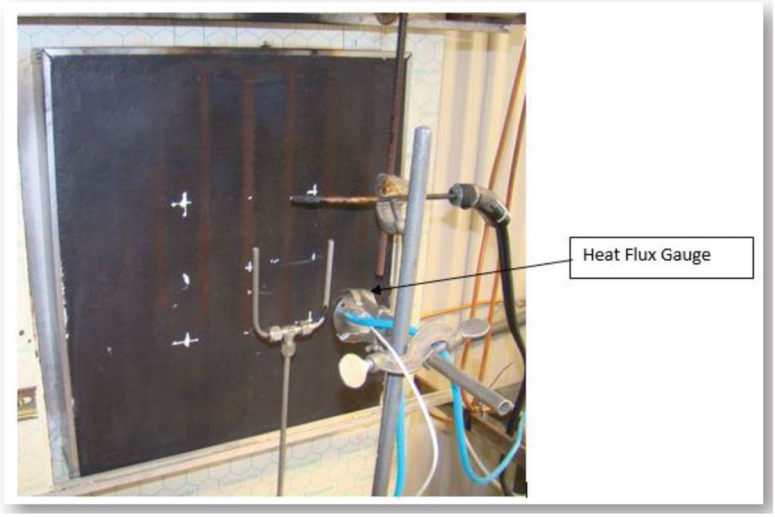

Figure 2.
Heat flux gauge.

Figure 3.
Metal holder with clips holding brattice material.

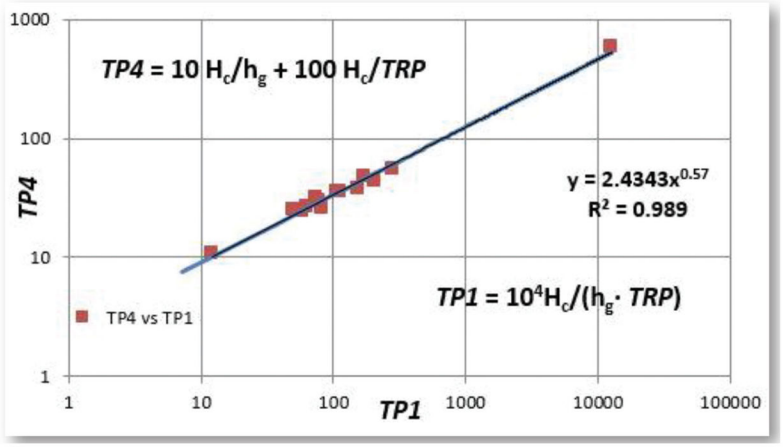

Figure 4.

The average values of the additive thermal parameter *TP4* plotted against the average values of the multiplicative thermal parameter *TP1*.

Min Eng. Author manuscript; available in PMC 2016 February 11.

Table 1

Average values for h_g and *TRP*, calculated from the experiments, along with values for the heat of combustion, H_C, and the minimum external heat flux for ignition, $(q''_e)_{crit}$.

Sample no.	Combustible material	Average heat of gasification, h_g (kJ/g)	Average thermal response parameter, *TRP*	Heat of combustion, H_c (kJ/g)	Critical heat flux, $(q''_e)_{crit}$(kW/m^2)
1	Brattice 1	12.2	227	18.5	15
2	Brattice 2	7.2	153	24.5	17
3	Brattice 3	Not measured	167	25.5	17
4	Brattice 4	30.9	301	22.7	20
5	Semirigid sealant	9.5	215	22.1	18
6	Foam sealant	7.7	46	25.0	12
7	PVC conveyor belt 1	14.4	150	23.4	11
8	PVC conveyor belt 2	14.9	Not measured	24.1	Not measured
9	SBR conveyor belt 1	23.2	241	33.0	15
10	SBR conveyor belt 2	22.1	244	28.2	16
11	SBR conveyor belt 3	15.3	256	24.8	17
12	SBR conveyor belt 4	20.3	226	25.8	15
13	SBR conveyor belt 5	11.2	386	22.3	23
14	Pine	7.7	242	14.9	16
15	Select pine	4.9	264	14.9	16
16	Oak	7.4	294	14.9	Not measured

Table 2

Average values of the thermal parameters *TP1* and *TP4*, calculated for each material. (N.D. = Not determined)

Sample no.	Combustible material	*TP1*	*TP4*
1	Brattice 1	82	26
2	Brattice 2	281	54
3	Brattice 3	N.D.	15
4	Brattice 4	12	11
5	Semirigid sealant	114	35
6	Foam sealant	12,783	587
7	PVC conveyor belt 1	74	32
8	PVC conveyor belt 2	154	38
9	SBR conveyor belt 1	N.D.	17
10	SBR conveyor belt 2	62	27
11	SBR conveyor belt 3	78	30
12	SBR conveyor belt 4	59	24
13	SBR conveyor belt 5	50	25
14	Pine	205	44
15	Select pine	169	47
16	Oak	106	36

Table 3

Ranking of the materials tested, from low to high hazard based upon the average values for *TP4* and *TP1*, respectively.

***TP4*: Material**	**Ranking**	**Average value**
Brattice 4	1	11
Brattice 3	2	15
SBR conveyor belt 1	3	17
SBR conveyor belt 4	4	24
SBR conveyor belt 5	5	25
Brattice 1	6	26
SBR conveyor belt 2	7	27
SBR conveyor belt 3	8	30
PVC conveyor belt 1	9	32
Semirigid sealant	10	35
Oak	11	36
PVC conveyor belt 2	12	38
Pine	13	44
Select pine	14	47
Brattice 2	15	54
Foam sealant	16	587
***TP1*: Material**	**Ranking**	**Average value**
Brattice 4	1	12
SBR conveyor belt 5	2	50
SBR conveyor belt 4	3	59
SBR conveyor belt 2	4	62
PVC conveyor belt 1	5	74
SBR conveyor belt 3	6	78
Brattice 1	7	82
Oak	8	106
Semirigid sealant	9	114
PVC conveyor belt 2	10	154
Select pine	11	169
Pine	12	205
Brattice 2	13	281
Foam sealant	14	12,783
Brattice 3	No data	-
SBR conveyor belt 1	No data	-